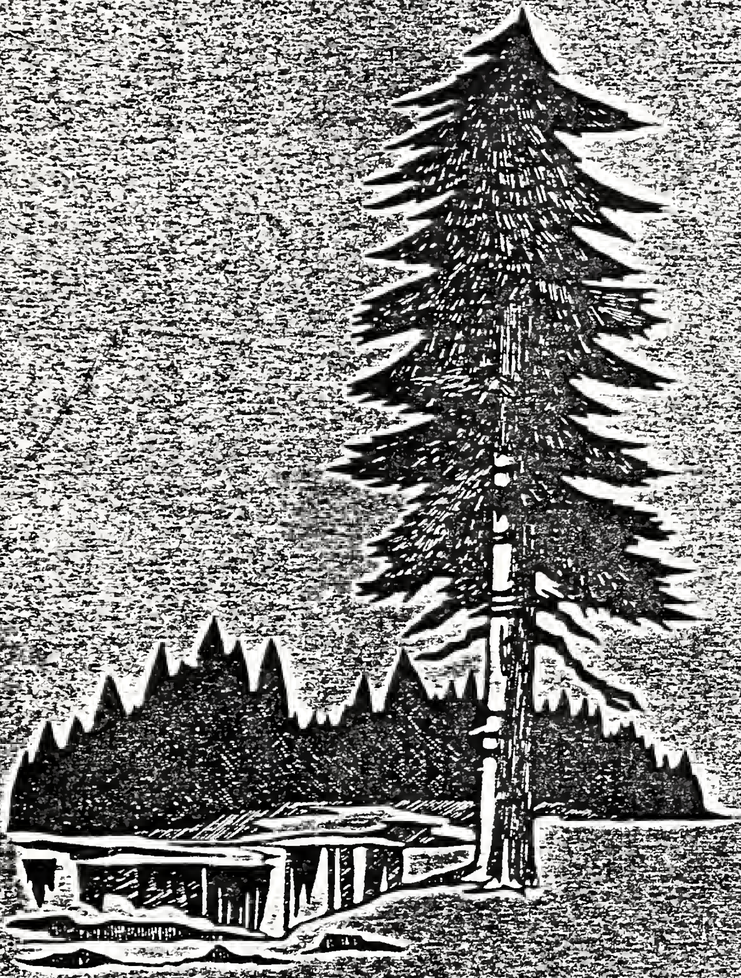
PROCEEDINGS OF WORKSHOP ON

SCHEDULING TIMBER HARVEST FOR

HYDROLOGIC CONCERNS



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Effects of Timber Harvest on Water Yield and Timing of Runoff - Snow Region

by

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Introduction

The hydrologic cycle (Figure 1) represent a complex series of process interactions which result in the translation of precipitation and energy inputs into, among other things, liquid and vapor outputs. The potential effect that various timber harvesting practices could have on water yield can be anticipated by evaluating the impact that the proposed activity can have on the processes involved with the translation of energy and water into the products of the hydrologic cycle.

The purpose of this paper is to evaluate the effects that timber harvesting has on water yield in areas where a significant portion of the precipitation input is in the form of snow. Most simply stated, forest harvesting directly modifies the evapotranspirational demands of the vegetation, usually reducing it, and the savings become water potentially available for streamflow. When snow is a significant form of the input, the change in the aerodynamics and energy balance of the stand, also associated with timber harvest, can alter the distribution of the input as well as the timing of its availability to the system. The form of the precipitation input greatly controls the nature and timing of timber harvest impacts on water yield. In this paper, we will consider the effect of timber harvest on water yield from the snow zones in the Rocky Mountain/Intermountain, Pacific Coast, and Central Sierra Regions. The following describes the snow conditions we are dealing with in those regions (Troendle and Leaf, 1980).

The Rocky Mountain/Intermountain region covers parts or all of South Dakota, Wyoming, Montana, Colorado, New Mexico, Arizona, Utah, and Idaho. Most of the water for the region comes from snowpacks which accumulate in winter and melt in summer. In general, winter temperatures are very cold, snow is dry, and snowpacks have a thermal gradient. That is, snow temperatures at the soil surface approach those of the soil itself (32°F or 0°C). Temperatures from the soil to the snowpack surface decrease, until at the air-snow interface they reach air temperature. However, this region is far from homogenous and the climatic differences affecting snowpack performance should be recognized.

The entire region is subject to summer thunderstorms which can cause disastrous flooding and assist in recharging the soil water supply. The entire area is usually subject to snow deposition as a result of high winds and dry snow, except for two major transition zones -- (1) northern New Mexico, southwestern Colorado, northern Arizona, and (2) northern Idaho. These are transition zones between the dry, low temperature snowpacks and continental frigid winter climate of the true Rocky Mountain chain, and the warm climate, wet snowpacks of the Pacific Coast. Dependent upon the direction from which the storms and air masses come, the snowpacks in these transition areas will be representative of one of the other major provinces all year; or they may resemble one province

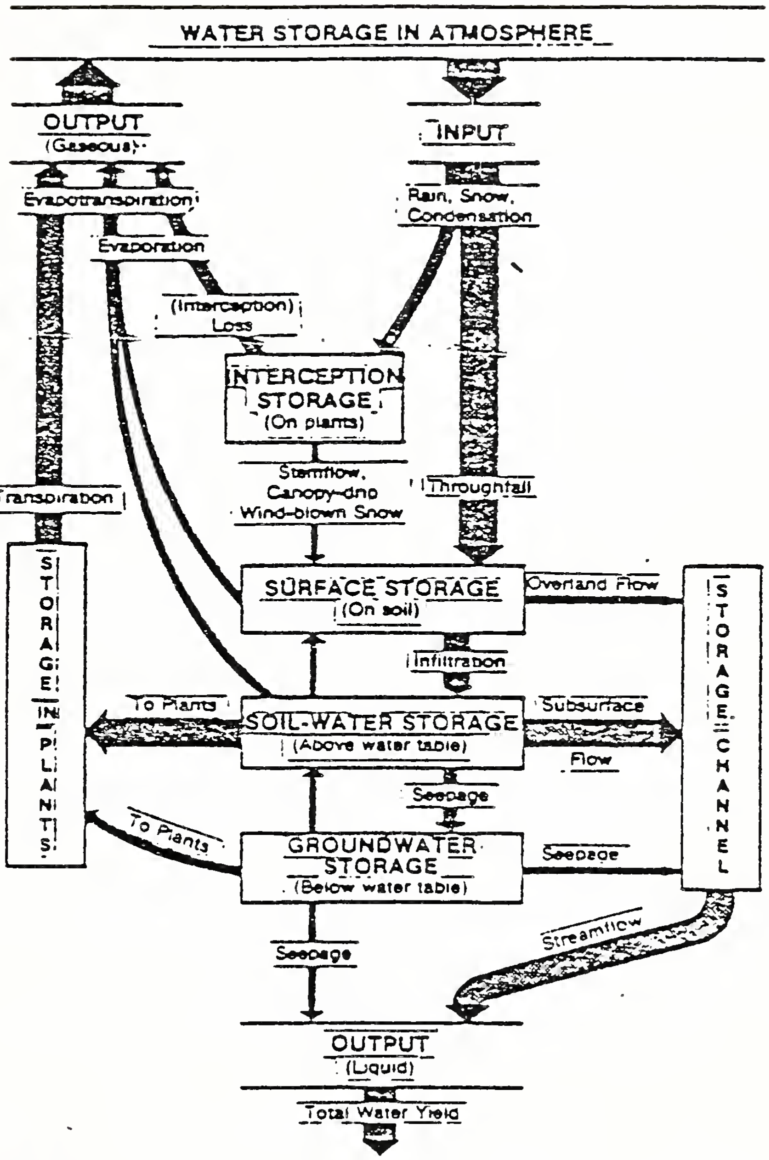

Figure 1 - The hydrologic cycle consists of a system of water storage compartments and the solid, liquid, or gaseous flows of water within and between the storage points (Anderson and others 1976).

during part of the year and resemble the other during another part of the year.

In western Montana and in Wyoming plains and rolling hills, there is enormous displacement and redeposition of snow. This affects evapotranspiration and tree growth since it removes the scanty snow cover from vast areas and concentrates it in a few locations. Obviously, this favors increased plant growth and water use in these sites. Evaporation (sublimation) loss from blowing snow is extensive.

Snows in the Rocky Mountains of Wyoming and Colorado and in the Wasatch Mountains are dry and cold. Wind redeposition is extensive in large, open areas. Particularly in Colorado, much of the mountain chain lies in the Alpine Zone. Snowpacks mature and melt in response to "ground heat" from below and to warm air temperatures and increased solar radiation in the spring. The thermal gradient in such packs creates unstable snow layers; frequent avalanching occurs from this cause and from melting snow sliding over wind slab formations. Since most melt occurs from the surface of the pack downward, the pack largely wets up from the surface. Most melt water goes directly into the soil. Since the packs are "cold," first melt goes to satisfying the thermal demand needed to bring the snowpack to a thermal equilibrium (32°F or 0°C) throughout the pack.

The shallow snows in northern Arizona frequently are redeposited by wind. Because of the lower latitude and higher insolation in winter, however, midwinter melt is often sufficient to wet the surface and prevent further movement.

Southwestern Colorado, northern Idaho, and the Rocky Mountains of western Montana receive wetter snows and even occasional rain. These cause some limited ice layering in the snow in southwestern Colorado.

The Pacific Coast region begins in the San Bernardino Mountains of southern California, continues northward through the Sierra Nevada of California, the Cascades of Washington and Oregon, and includes the mountain ridges and peaks of western and central Nevada. The same type of snowpacks occur northward through British Columbia and into southeastern Alaska, at least to Anchorage.

The maritime climate in the winter is warm and wet. Summers vary depending upon the particular portion of the province, but generally they are dry with little or no summer precipitation. Summer thunderstorm activity is extensive over the southern Sierra Nevada, adding some water to that area, largely in the relatively treeless alpine area. The remainder of the Pacific Coast province, with the exception of parts of Washington, receives little summer precipitation.

Fall and winter precipitation is normally snow, but extensive rainstorms sometimes occur up to 2436 m (8,000 ft) elevation in the Central Sierra. Significant snow falls at elevations down to 1218 m (4,000 ft), and, on rare occasions, significant amounts fall to 610 m (2,000 ft). Rains remove snowpacks up to 1827 m (6,000 ft) elevation and infrequently remove significant parts of the packs to over 2132 m (7,000 ft).

Snowpack depth is extremely variable and has been measured at maximum pack from 91 cm (36 in) to over 700 cm (275 in).

Snow redistribution normally does not occur due to the wetness of the snow.

Snow metamorphism continues all winter as a result of the warm climate, and frequent ice lenses occur throughout the packs, particularly on south, open slopes. Temperatures normally remain at 0°C throughout the packs. When rain falls on packs significantly lower than 0°C, serious flooding can occur from rain and melt water flowing over the frozen layer (Smith 1974).

Snowpack configuration of these warm, wet snows typically consists of a mixture of heavy and light density layers having different maturation schedules and water-holding capacities. The configurations vary dramatically by aspect and by forest cover (Smith 1974, 1975).

Because of warm climate, frequent rains, and melting snow, snowpacks in the subalpine are usually wet and remain at thermal equilibrium throughout the snow season. Frequent snowfalls keep the albedo high (80-90) until spring melt out is well under way, at which time albedo drops to about 45 percent. Major winter melt is caused more from absorption of solar radiation by the rocks, trees and shrubs standing above the snow than from direct solar radiation to the pack. These, in turn, heat up and radiate sensible heat to the pack. This creates the major melt until late season low albedos of the snow increase radiation absorption by the pack.

Because of the isothermal, wet condition of the snow, forest cover change can be used to direct heat into or away from the snow. Melt out date can be moved forward or backward 2 weeks to 1 month by increase or decrease of forest cover (Smith 1974, 1975).

While wind distribution plays little role in this province, differential melt is substantial. The greater amount of snow in forest openings on the west-south walls were once thought to be the result of distribution; it has since been found to be the result of greater melt on the north and east side of the opening (Smith 1974).

There are more problems associated with evaluating the hydrologic responses of snow covered basins to timber harvest than those subject to rainfall.

Snowfall redistributes the precipitation in time and occasionally in space. Snow falling in the Rocky Mountains is not reflected in the soil moisture or streamflow until spring melt. In the Pacific Coast province it may appear as soil moisture or streamflow within a few days, or it may not appear until spring. Due to lack of ice lenses, melt or rain falling on snow in this region may enter the soil under a forest growing on a south slope. Removal of the forest may result in ice lens formation in the pack, and rain or melt may flow through the snow to the stream and never reach the soil to provide water for satisfaction of soil water deficit.

The Fool Creek Experiment

Anderson et al. (1976) summarized the findings of numerous watershed experiments designed to evaluate the effects of forest harvesting on streamflow. Most of those reported experiments were conducted on "rain dominated" watersheds as there is a paucity of information, by comparison, for "snow dominated" watersheds. One experiment, Fool Creek, in the Colorado subalpine, stands out because of its longevity and completeness. I will try to update the results of the Fool Creek experiment with respect to the effects of timber harvest on the timing and quantity of streamflow and at the same time compare or contrast those findings with others in the snow zone region of the western United States.

The Fool Creek Experiment is a classic paired watershed study that has been ongoing at the Fraser Experimental Forest since the early 1940s. The streamgage on Fool Creek, the 289 ha (714 acre) treatment watershed, was built in 1941 while the gage on the companion East St. Louis Creek, the 803 ha (1984 acre) control watershed, was built in 1943. The watersheds were calibrated until 1952 when the timber harvest access system was built on Fool Creek. Approximately 14 ha (35 acre) of the 289 ha watershed was impacted by roads and log decks. The watershed was harvested in 1954, 1955 and 1956. Approximately 40 percent of the watershed was harvested using alternating cut and leave strips which varied from 1 to 6 tree heights wide (Figure 2). The treatment itself has been thoroughly described by Goodel (1959), Leaf (1975), and Alexander and Watkins (1975).

The objective of the experiment was to determine the impact, if any, that forest harvesting had on total precipitation input to the watershed, the distribution of input with respect to openings and opening size within the watershed, and the effect that harvesting has on total yield and timing of streamflow. Snow courses were monitored on both watersheds annually from 1943 to 1954 to "calibrate" the relationship of peak water

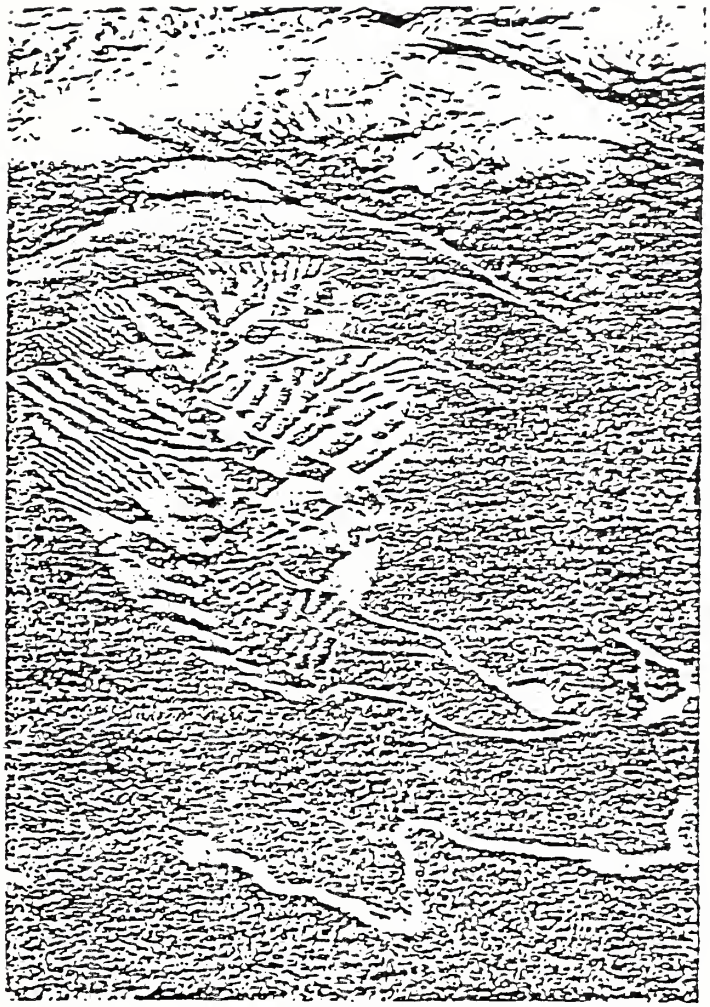

Figure 2 - Fool Creek watershed, Fraser Experimental Forest. East St. Louis Creek, the 1,984-acre control watershed, is to the right of Fool Creek (Leaf, 1975).

equivalent on the two watersheds. Postharvest data was collected in 1959, and from 1966 to 1978. Figure 3 presents the pre- and post-treatment estimates of peak water equivalent on Fool Creek plotted over that for East St. Louis. A covariance analysis of the slopes of the pre- and post-treatment relationships indicates no significant change in the relationship occurred following harvest. It can be noted however, that the estimate of the average water equivalent on Fool Creek increased by over 5 cm (2 in) following harvest. The inference that can be drawn is that although the distribution and dissipation of input was altered by harvest, the total input, on a watershed scale, was not significantly altered. It should also be noted that a re-evaluation of the data from Wagon Wheel Gap (Leaf, 1975) also indicated the total input to that watershed was not altered following harvest. There is no indication that timber harvest increases or decreases the total input to the system on a watershed scale. Intensive surveys in the cut and leave strips on Fool Creek were consistent with earlier studies (Wilm and Dunford, 1948) on the forest where it was found that there was a significant increase in snow accumulation in the forest openings. After evaluating the potential interception losses from the canopy as well as evaluating the effect of changing the aerodynamics of the stand through cutting, it was concluded that the increased accumulation in the cut strips was more the result of redistribution than savings in interception (Hoover and Leaf, 1967) and that the size of the strip or opening alters the trapping efficiency. Hoover (1969) felt that for optimal distribution the opening should not exceed 8 tree heights in width. To further refine the estimate of optimal size, data from Fool Creek (Figure 4) imply that the pack in the center of larger openings (6 H) can be scoured. The mirror-like image of the comparison of water equivalent between forest and open (Figure 4) has lead Leaf (1975) to conclude that in the Colorado subalpine the contributing area for the additional snow in the open is an area downwind of the opening and approximately equal in size. Gary (1974) made similar observations at a study site in southern Wyoming.

After numerous re-surveys of the cutting plots reported on by Wilm and Dunford (1948), intensively surveying the cut and uncut strips of Fool Creek, and evaluating other pertinent observations; Leaf (in Troendle and Leaf, 1980) constructed a redistribution relationship for openings in Rocky Mountain subalpine forest. The redistribution (ρ) function is shown on Figure 5 and as can be noted, it implies that a 5 H opening is optimal for maximizing the accumulation of snow. The RHO (ρ) function for the most part represents the current state-of-the-art in understanding the effect of forest harvesting on snow redistribution in the Colorado subalpine. These findings are not necessarily consistent with findings elsewhere in the snow region, however where snow may not be as light. Golding and Swanson (1978) recently reported on observations on replicated plots in lodgepole pine along the James River in Alberta, Canada. They found that 2 - 3H openings were optimal for redistribution. However, their larger openings (5 - 6H) were still nearly as efficient in trapping

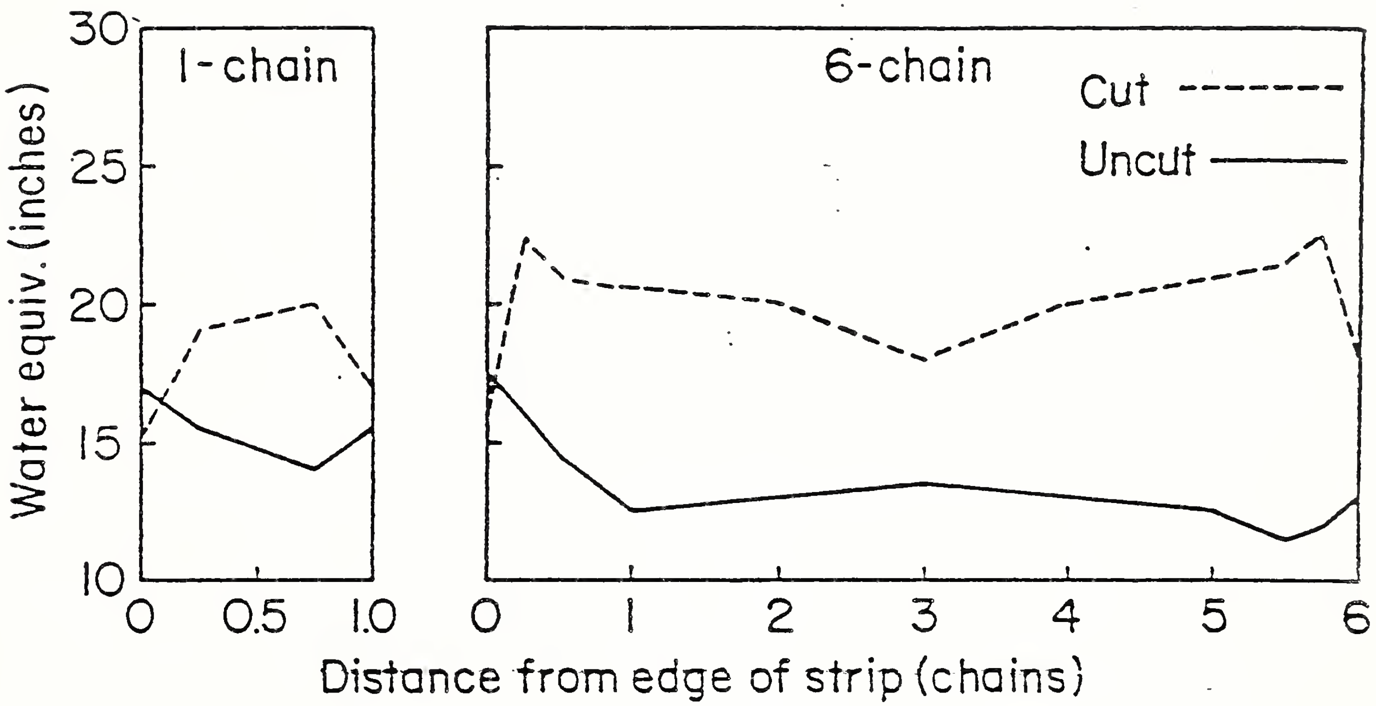

Figure 4 - Comparison of average snow accumulation in one and six tree-height strips on Fool Creek, Fraser Experimental Forest (Leaf, 1975).

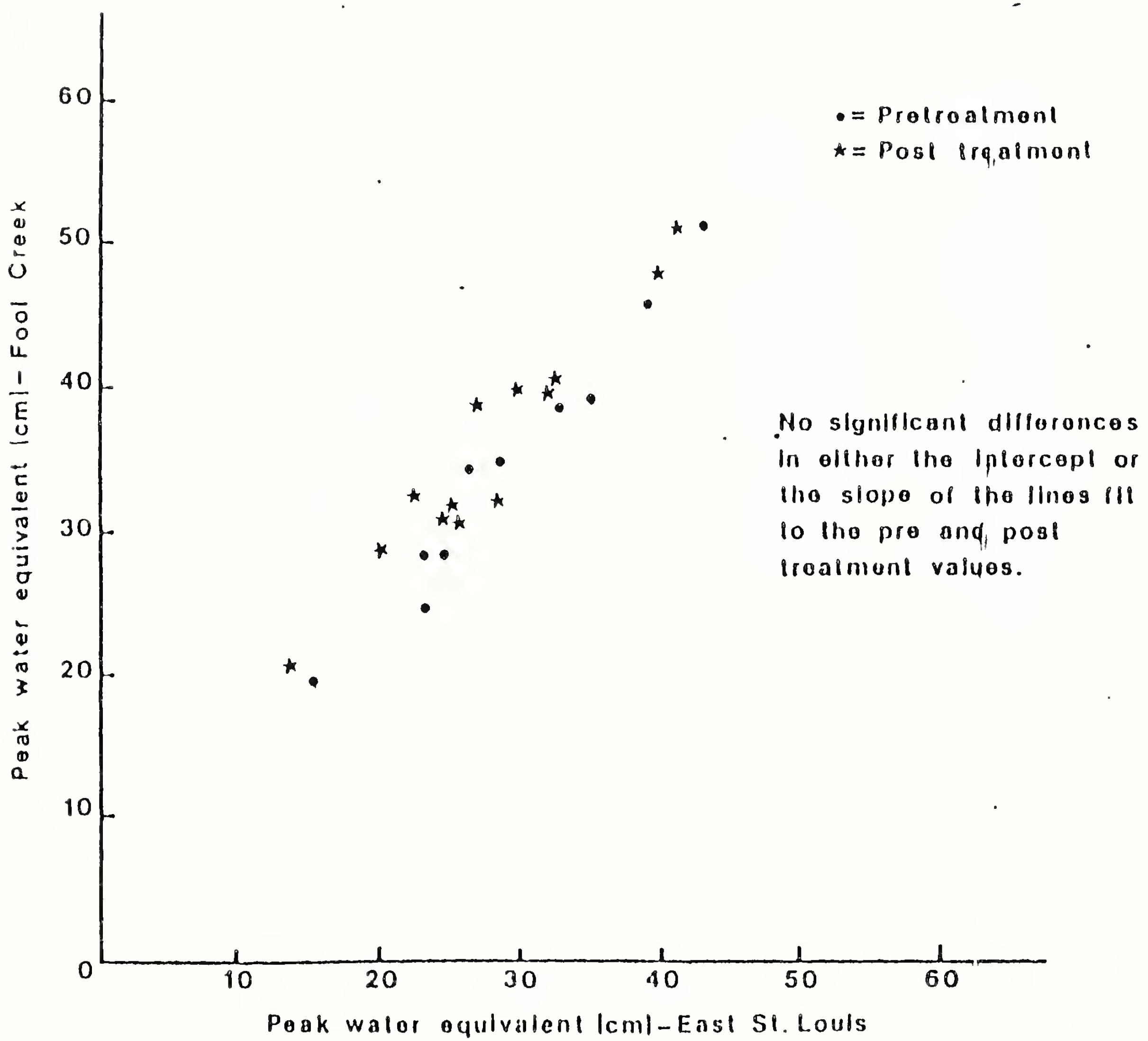

Figure 3. - Peak water equivalent in snowpack on Fool Creek and E. St. Louis Creek under pre and post treatment conditions.

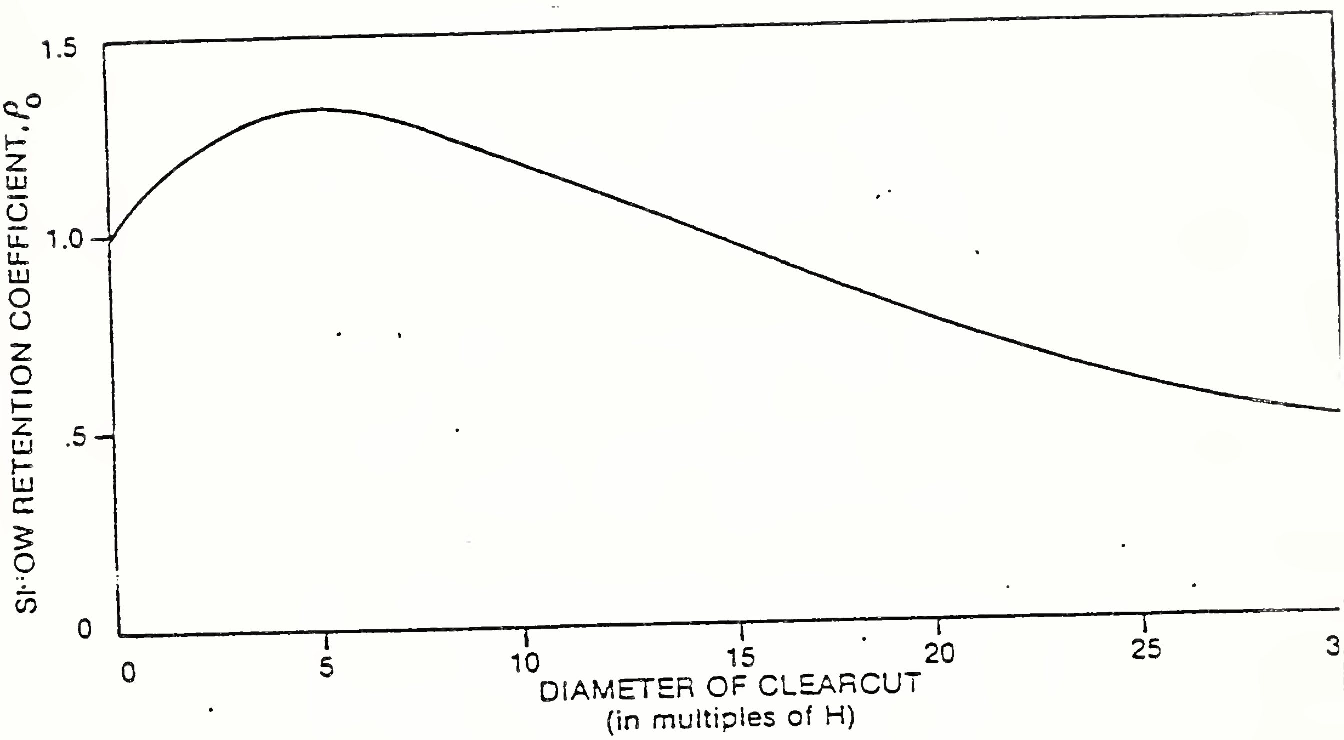

Figure 5 - Snow retention as a function of size of clearcut. H is the height of surrounding trees (from Troendle and Leaf, 1980).

snow as the smaller ones. In contrast to some of the Fraser findings, Haupt (1979) concluded that a significant portion of the 56 percent increase in snowpack on north facing clearcuts in northern Idaho resulted from interception savings.

It can be concluded that we still need more understanding of the processes of snow redistribution and interception and the role that they directly play in generating the observed changes in flow. Much depends on the susceptability of the snow to being wind blown or re-distributed.

In those portions of the snow zone where the snow is light and dry, the redistribution phenomenon is quite significant, and reasonably consistent. By nature, interception losses are minimal, as are potential savings. As the snow becomes heavier and wetter, redistribution is less significant. Wet snow sticks to the folliage and interception loss increases.

The longevity of the effect on accumulation is quite significant. Twenty-three years after harvesting Fool Creek, the impact is not different than implied in either Figures 4 or 5. Haupt (1979a, b) found little if any change in snow accumulation gains during the 34 year study in northern Idaho. Gary (1979) found that the effect can persist for decades or perhaps the life of the residual stand. Leaf and Alexander (1975) using a simulation model concluded the effect could last at least 50 - 60 years.

In summary, snow redistribution due to changing the aerodynamics of the stand can be quite significant and may persist until the replacement stand is three-fourths or more the height of the residual stand. It is not known however, how much of the observed change in streamflow can be attributed to the efficiency of redistributing input versus the reduction in evaporative losses. Meiman and Dietrich (1975) working in Colorado estimated 80 percent of the potential change is due to an ET modification while only 20 percent can be attributed to the efficiency of redistribution.

Changes in Streamflow

Figure 6 represents the average hydrograph for Fool Creek for pre (1942-55)- and post (1956-67)-harvest periods. It is immediately apparent that the advance melting due to the openings caused the hydrograph to rise quicker with little if any subsequent effect on the recession hydrograph. As will be noted, the increase in flow due to the treatment has since averaged 7.4 cm (2.9 in) for the last 23 years. All of this increase occurs on the rising side of the annual hydrograph. A regression analyses of the post-treatment relationship between the treatment and control watershed indicated that a reduction in flow due to vegetative recovery or time is now significant. Two models were fit to the 23 years of postharvest data. The first was:

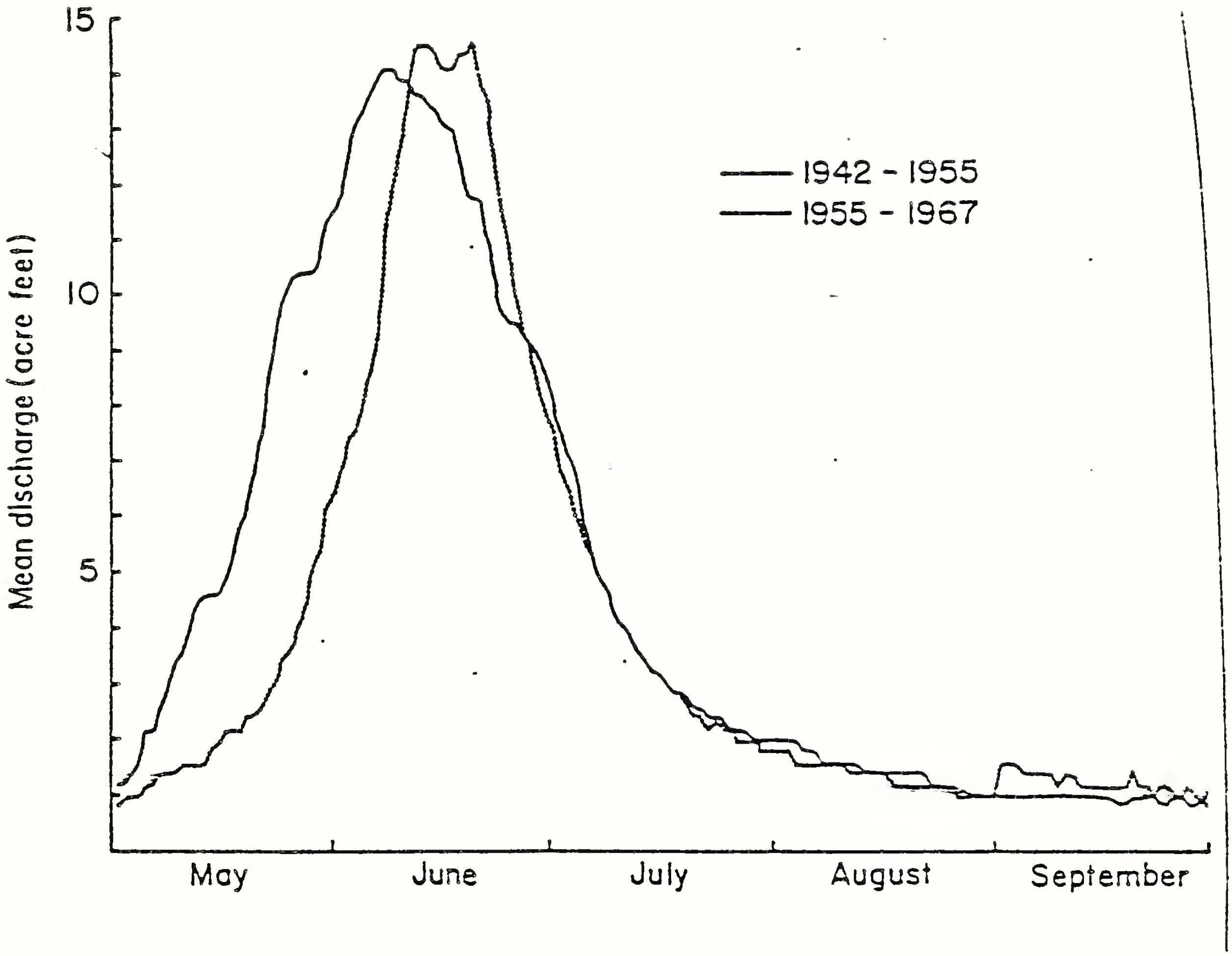

Figure 6 - Average hydrographs for Fool Creek watershed. Dotted line is the average hydrograph for 1942-55, before timber harvest. Solid line is the average hydrograph for 1955-67, following timber harvest (from Leaf, 1975).

$$Q_{\text{Fool Creek}} = \beta_1 Q_{\text{E. St. Louis}} + \beta_2 t$$

where

$Q_{\text{Fool Creek}}$ = Annual flow from Fool Creek in cm.

$Q_{\text{E. St. Louis}}$ = Annual flow from the control watershed, East St. Louis, in cm.

t = A linear variable for time, in years, since treatment.

The second model was similar to the first with the exception that a quadratic function for time (t^2) was used. The fit of both models was basically the same. The standard error of the mean for the linear model was 0.3 percent smaller than that for the quadratic model. Complete recovery is estimated as requiring 52 years using the linear and only 35 years using the quadratic model. Neither estimate can be expected to be correct and more will be said about recovery later. Figure 7 shows the pre- and post-treatment relationship of annual flow from Fool Creek and East St. Louis Creek. The annual changes in flow, resulting from the treatment and estimated using the linear function for time are shown in table 1. The average change in flow over the 23 year period was 7.4 cm (2.9-in) but was very heavily dependent on total flow. The expected first year increase in flow (t=1) using the linear function for time and the mean flow for the control watershed (of 34 cm or 13.4 in) during the post-treatment years is 9.4 cm (3.7 in). The reduction in the first year increase that can be attributed to the past 23 years (t=23) of time is 4 cm (1.6 in). We would then expect a 5.3 cm (2.1 in) increase in flow this year (t=24) given the mean flow of 34 cm on the control watershed. However, it should be noted that if 54.3 cm (21.4 in) of flow were to occur on the control watershed next year, (the highest flow during post treatment record) we could still expect a 10.9 cm (4.3 in) increase in flow on Fool Creek. In summary, 40 percent of the watershed was harvested and the increase in flow has been approximately 40 percent. Other experiments in the snow zone, yield somewhat similar results.

At Wagon Wheel Gap in the headwaters of the Rio Grande in Colorado, Bates and Henry (1928) observed accelerated snowmelt rates after clearcutting the aspen-mixed conifer forest from one 81 ha (200-acre) watershed. This effect was apparent in the streamflow hydrograph (fig. 8). Moreover, annual water yields were increased about 22 percent during the 7-year period that records were taken after harvest cutting. Swanson and Hillman (1977) working in West-Central Alberta used the findings at Fool Creek and Wagon Wheel Gap to fashion a predictive procedure to estimate the changes in volume and timing of flow following clearcutting. After comparing nine logged and unlogged catchment pairs, they observed 59%

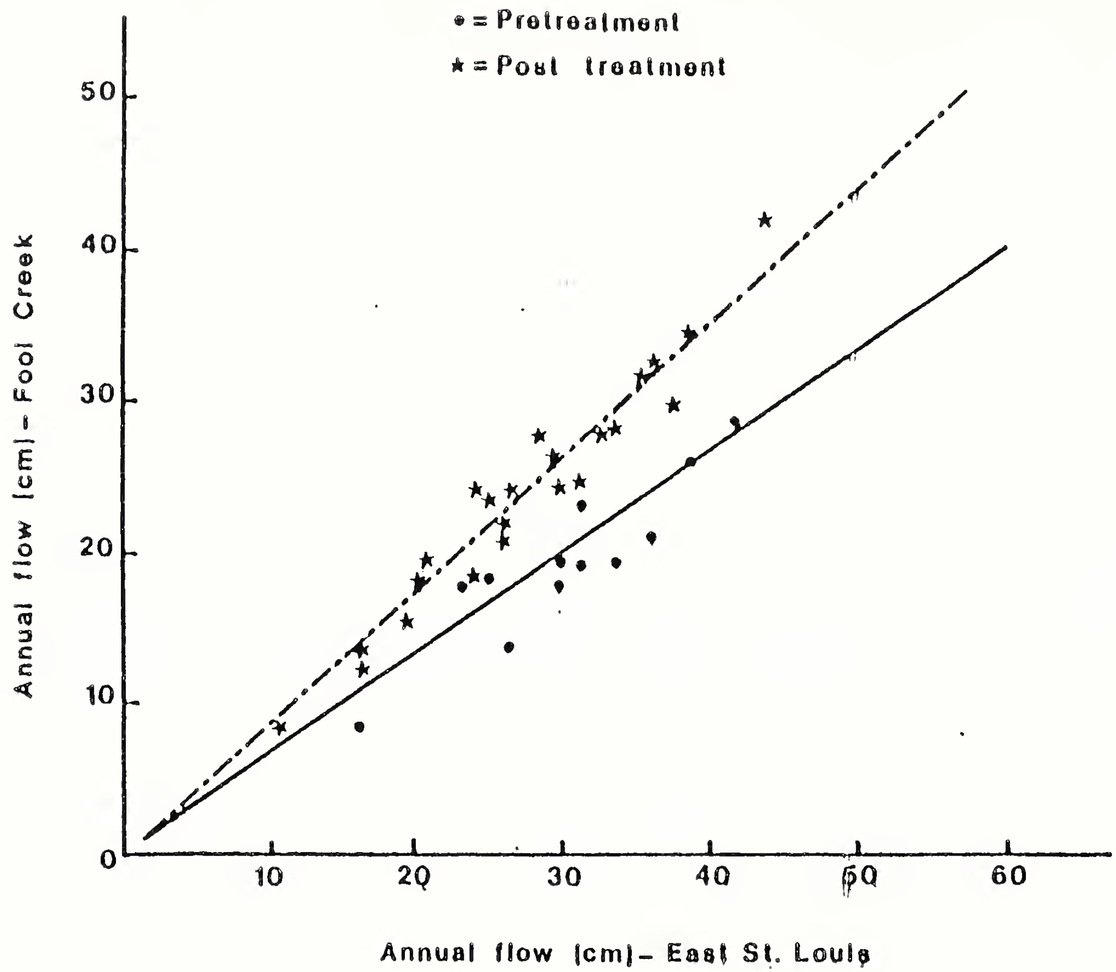

Figure 7. - Annual flow from Fool Creek and E. St. Louis Creek under pre and post treatment conditions.

Table 1. April to September streamflow from Fool Creek and an estimate of the increase due to timber harvest.

Year	Observed Runoff		Estimated[1/] Increase	
	cm	(In.)	cm	(In.)
1956	35.3	(13.9)	10.9	(4.3)
57	52.8	(20.8)	14.7	(5.8)
58	30.5	(12.0)	8.9	(3.5)
59	30.3	(11.9)	7.6	(3.0)
60	34.8	(13.7)	9.1	(3.6)
61	24.4	(9.6)	6.1	(2.4)
62	43.9	(17.3)	12.2	(4.8)
63	10.9	(4.3)	2.3	(0.9)
64	22.9	(9.0)	5.6	(2.2)
65	39.6	(15.6)	10.7	(4.2)
66	17.3	(6.8)	3.6	(1.4)
67	27.9	(11.0)	6.8	(2.7)
68	23.1	(9.1)	6.1	(2.4)
69	30.7	(12.1)	7.9	(3.1)
70	27.6	(14.8)	10.4	(4.1)
71	40.2	(15.8)	9.9	(3.9)
72	29.7	(11.7)	5.7	(2.2)
73	31.0	(12.2)	7.6	(3.0)
74	35.0	(13.8)	7.9	(3.1)
75	26.4	(10.4)	5.6	(2.2)
76	19.6	(7.7)	2.8	(1.1)
77	15.7	(6.2)	1.8	(0.7)
78	32.8	(12.9)	6.1	(2.4)
$\bar{X}$	30.0	(11.8)	7.4	(2.9)

[1/] Estimate of change is made using linear function of time (t=year since harvest) in equation $\Delta Q_{\text{Fool Creek}} = 0.280\ Q_{\text{East St. Louis}} - .180\ t$

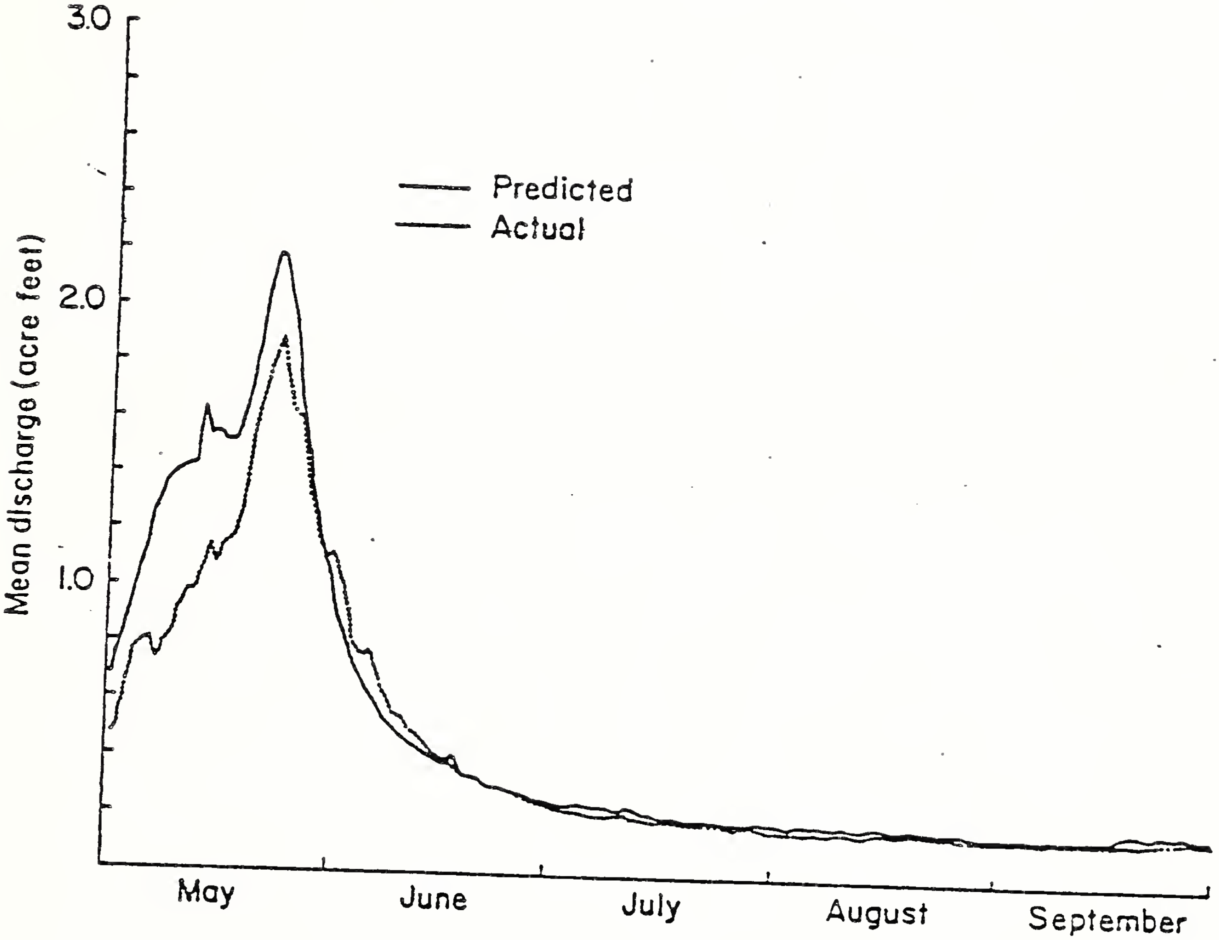

Figure 8 - Average hydrographs for Wagon Wheel Gap watersheds (Bates and Henry 1928). The dotted line is the predicted hydrograph for watershed B if not harvested, based on pre-harvest regression for 1912-19. Solid line is the actual hydrograph for watershed B after timber harvest.

more water in melt runoff, 27% greater yield and 1 1/2 - 2 times greater storm peaks from watersheds where 35 - 85 percent of the area was cut. The nature of the response was similar to that for Wagon Wheel Gap and is shown on Figure 9.

Peak Discharges

A covariance analysis of peak daily discharge between Fool Creek and East St. Louis indicated no significant change. However, the estimate of average peak daily discharge, for after treatment, did increase .02 m^3/sec (1 CFS) from .26 to .28 m^3/sec (9 to 10 CFS/day). Individual rainfall events are so few at Fraser Experimental Forest that unlike the Alberta study (Swanson and Hillman, 1977), detection of changes in storm response cannot be attempted. The pre- and post-treatment relationship in peak discharges for Fool Creek and E. St. Louis is shown on Figure 10. Swanson and Hillman (1977) did observe increases in summer storm hydrographs. Response potential is similar in the "Snow Zone" to that in the "Rain Zone." The most significant difference is the usual lack of rainfall in the snow zones during the growing season.

Summary

In summary, timber harvesting in the "Snow Zone" reduces the evapotranspirational draft. This reduces soil moisture depletion during the growing season and resulting deficits are far less going into the winter than prior to harvest. During the spring snowmelt period, the soil moisture deficit to be satisfied is reduced because of the reduced ET the summer before and more water is available, during the recharge period, for streamflow. As a result, most of the increases in flow observed at Fool Creek or Wagon Wheel Gap were from the spring melt. Since radiation is the chief source of energy to melt snow (Garstka, et al, 1958) opening the stand enhances melt and causes much of the pack to become streamflow very early in the season as noted earlier. In addition to the change in timing, there is an apparent increase in "efficiency" associated with the advanced melt as well. In many portions of the region, more snow is accumulated in the openings either through redistribution (Leaf, 1975) or by savings in interception losses (Haupt, 1979a). The snow in the opening melts earlier, up to a month earlier on high energy sites, and is made available for storage or for streamflow very early and during the time of peak recharge when minimal transpirational draft is occurring. As a result, the efficiency of converting snow pack to streamflow is very great and the melt water has little opportunity to be "lost." Because of this interaction it is difficult to define what portion of the observed changes in flow from "Snow Zones" can be attributed to ET savings and which can be attributed to the "efficiency" of the redistribution of the pack and desynchronization of its melt rate.

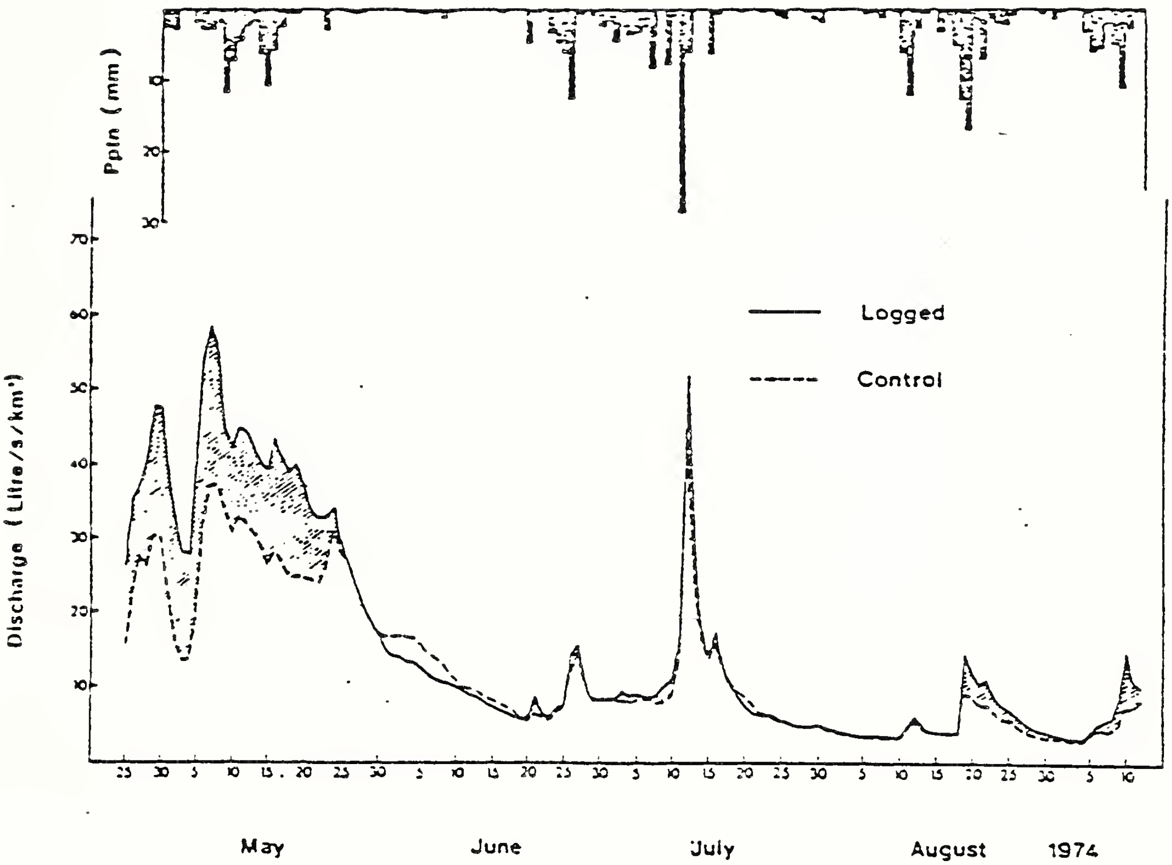

Figure 9 - Composite hydrographs for 1974 from nine logged and nine control catchments on the study area. Shaded portions indicate times when logged yield exceeded control (from Swanson and Hillman, 1977).

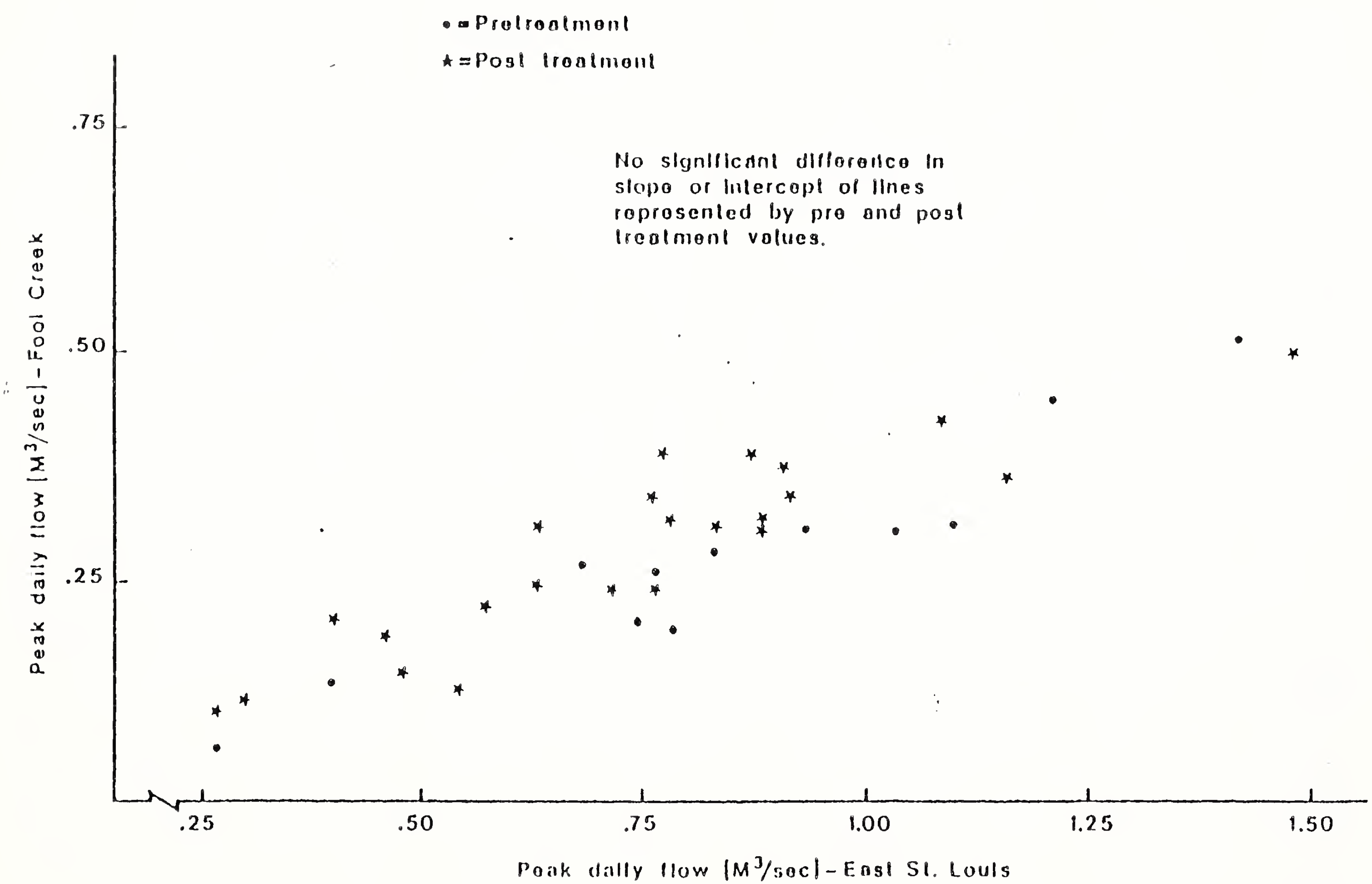

Figure 10. - Peak daily discharge from Fool Creek and E. St. Louis Creek, under pre and post treatment conditions.

As noted earlier, Meiman and Dietrich (1975) concluded that 20 percent of the potential change could be attributed to redistribution in lodgepole pine on the Colorado front range.

Because the redistribution effect can be so long lasting (Gary 1979, Haupt 1979a & b, Swanson and Hillman 1977, Leaf and Alexander 1975), it is difficult to predict the actual longevity of harvesting effects on streamflow. On Fool Creek, for example, a linear time model estimates 52 years are required for recovery while 35 years are estimated if the quadratic function is used. Neither of these can be expected to be correct. What we have evidenced so far in the record is probably only the impact that vegetative recovery has had on the ET process. Whatever was the effect of redistribution itself, is probably still in effect and we can expect it to continue for some time.

The shape of the expected recovery curve, for watersheds such as Fool Creek, is complex. At first the slope of the recovery line will be quite minimal as a new stand establishes. In the case of Fool Creek the first 17 years of post harvest record did not express a significant trend in the reduction of increased flow (Leaf, 1975). This establishment period is then followed by a period of rapid reduction. This period should also tail-off and reflects what is being observed now on Fool Creek. We can expect that the effect of redistribution will hold the curve above zero for quite sometime into the future.

Predictive Techniques

Within the "snow zone," only one "complete" hydrologic model has been demonstrated to be a useful management tool in the region as a whole. Leaf and Brink (1973a, 1973b) have developed a comprehensive hydrologic model which simulates the water balance in several hydrologic subunits within a subalpine watershed on a continuous year-round basis, and compiles the results from up to 25 subunits into a "composite overview" of the entire drainage. The model has been specifically designed to simulate watershed management practices and their resultant effects on hydrologic system behavior.

Leaf and Alexander (1975), and Leaf (1975) have described the application of the model to timber scheduling decisionmaking in the lodgepole pine and spruce-fir types of the subalpine. Alexander and Watkins (1975) have described a pilot study on Deadhorse Creek, Fraser, Colorado, which is intended to verify the simulated results.

However, the model may be too data demanding for everyday use in planning activities. The level of expertise required to operate it is also quite high. As a result models like the Sub-Alpine Water Balance Model (WATBAL) are tools that we need available to us but

are ones that may see limited practical application. However, WATBAL is one of the models used to develop WRENS (Troendle and Leaf, 1980) techniques for hydrology. Gordon Snyder will discuss this effort in detail as it represents one way that the knowledge gained from research can be organized into a series of predictive techniques, more useful to the manager, than the simulation models themselves.

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